Forest Ecology and Management 426 (2018) 7–17

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Long-term (33 years) rainfall and runoff dynamics in a tropical dry forest ecosystem in western Mexico: Management implications under extreme hydrometeorological events☆

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ARTICLE INFO

Keywords:
Chamela
ENSO
Forest management
Hurricane
ILTER
Mex-LTER
Rainfall:runoff relationship
Tropical dry forest

ABSTRACT

Rainfall, runoff and sediment yield have been measured over three decades (1983–2015) in five contiguous small watersheds (12–28 ha) covered by mature tropical dry forest (TDF) at the Chamela Biological Field Station, UNAM, in the southern Pacific Coast of Jalisco, Mexico. Hydrological dynamics strongly drive the seasonal and inter-annual variability of TDF primary productivity, litter decomposition and nutrient cycling. Although the study region is constantly influenced by storms related to hurricane activity, they rarely make landfall. However, hurricanes have landed twice over a four-year period in the reserve: category 2 Hurricane Jova, in October 2011, and category 4 Hurricane Patricia, in October 2015. The long-term data has allowed to evaluate ecosystem's response to these two major hydrometeorological events, in the context of the historic rainfall/runoff pattern. The results showed that antecedent precipitation and rainfall intensity were the major factors controlling rainfall-runoff and soil erosion processes. The analysis also showed the timing of the onset of the rainy season was very regular but the length of the rainy season was quite variable. The highly variable rainfall pattern and high probability of intense storms at the onset of the wet season were linked with the vulnerability of TDF to soil erosion. Also, two types of recurrent and intense drought periods have been identified: the high inter-annual droughts; and the frequent within-wet season droughts ("canículas"). There is a clear influence of the "El Niño"-Southern Oscillation phenomenon (ENSO) on the study area, with lower annual rainfall during its hot phase, and higher annual rainfall during its cold phase ("La Niña"). The relevance of these findings is discussed in terms of forest ecosystem management practices in the region and its implications concerning the current climate-change forecast for the study area.

1. Introduction

Water has an important integrative role in most terrestrial ecosystems, making its dynamics a key aspect for ecosystem structure and functioning, and as a major controlling factor on ecosystem productivity (Chapin et al., 2002). Maintaining natural water dynamics has been an essential ecosystem management component and a requirement to reach sustainable productivity. Understanding hydrological processes in tropical dry forest (TDF) is particularly important since water is the major limiting resource in these ecosystems (Bullock et al., 1995; Dirzo et al., 2011). However, there is a paucity of literature concerning the hydrological characterization of TDF (Maass and Burgos, 2011). Studies of hydrological processes in TDF represent less than 1% of the published forest hydrology literature (Farrick, 2014).

There is a robust response of the hydrological cycle to global warming (Held and Soden, 2006). IPCC Report (2014) indicates that "*Changes in many extreme weather and climate events have been observed since about* 1950". Also, the report forecasts "*an increase in the number of heavy precipitation events in a number of regions*". Although Knutson et al. (2015) forecast fewer tropical cyclones globally in a warmer late-

☆ This article is part of the Special Issue "Resilience of tropical dry forests to extreme disturbance events: An interdisciplinary perspective from long-term studies" published at the journal Forest Ecology and Management 426, 2018.

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http://dx.doi.org/10.1016/j.foreco.2017.09.040
Received 1 July 2017; Received in revised form 15 September 2017; Accepted 16 September 2017
Available online 23 September 2017
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twenty-first-century climate, they project an increase in average cyclone intensity, precipitation rates, and the number and occurrence of very intense category 4 and 5 hurricanes. In Mexico, TDF regions are already experiencing extreme meteorological events. Álvarez-Yépiz, J.C.,Martínez-Yrízar, A., (2015) reported an extreme frost in 2011, causing unprecedented tree mortality in the most northern distribution of TDF of Sonora and Sinaloa. Also, they mentioned that hurricane activity in the Pacific coast of Mexico has increased significantly in the last decades. Seven hurricane events have struck the Jalisco Coast since 1949. An extreme one in Manzanillo (100 km south of Chamela) caused 1500 deaths in 1959. In 2011 for the first time since the Chamela TDF ecological monitoring started, the study site was directly impacted by Hurricane Jova (category 2). Four years later (2015), Hurricane Patricia made landfall, but with a much-stronger wind force (category 4; see Parker et al., this issue). This increase in hurricane frequency in tropical areas has triggered an interest to study the effects of extreme meteorological events and their implication for forest management and conservation.

TDF is the most extensive tropical ecosystem in the world, originally representing 42% of all tropical forests (Murphy and Lugo, 1986). Large areas of these forests are found in India, Africa ("miombo" forest), Australia, northeastern Brazil ("caatinga" forest), northwest Argentina ("chaco" forest) and along the Pacific coast of Mexico and Central America ("selvas bajas caducifolias"). In Mexico, TDF is well represented, covering originally $> 24 \times 10^6$ ha distributed along the Pacific coast, northern Yucatán Peninsula, Balsas Basin, southern tip of Baja California Peninsula, and large areas in Tamaulipas (Rzedowski, 1978; Trejo, 1998; Trejo and Dirzo, 2002).

Despite the biological and economic importance of TDF, it has seen deforestation at alarming rates, mainly by pasture-land expansion during the second half of last century. This has caused forest degradation, particularly in sub-humid areas of Latin America (Toledo, 1991) and disruption of ecosystem services (Maass et al., 2005). According to INEGI (2005 and INEGI 2013) 69.4% of the original TDF distribution has been already lost. Janzen (1986) considered TDF as one of most endangered major tropical ecosystems, and warned in the early 80 s, that less than 0.1% of the original tropical dry forest in Pacific Mesoamerica had real conservation status. This deforestation trend triggered an important TDF conservation process (e.g. Ceballos and García, 1995; Taber et al., 1997). However, in a more recent study, Miles et al. (2006) estimated that little over 1 million km^2 of tropical dry forest remained on earth. They warned that 97% was still at risk even though about 30% was under some form of protection (70% in South America) – they also noted that climate change was an important risk for TDF conservation.

To improve the understanding of the structure and functioning of TDF, and to develop ecologically sound management practices for its sustainable use, a long-term ecosystem research project was established in 1981 (Sarukhán and Maass, 1990; Maass et al., 2002) within a well-protected TDF of the Chamela Biological Station of the National Autonomous University of Mexico (UNAM). Since then, inputs, outputs and internal fluxes of water, energy, carbon and nutrients have been monitored on this ecosystem for more than three decades. The study site has been preserved from human perturbation. However, the forest is subject to the effects of natural disturbances such as droughts and hurricane activity, but not natural fires. The interest in extreme meteorological events in TDF research and monitoring, is also shared by land managers, as well as the inhabitants of the area.

A detail understanding of the TDF hydrology, especially the timing of rain onset and the possibility of droughts of several sorts, will help local land managers maximize productivity and avoid crop failures. Therefore, the aim of this paper is fourfold: (1) to quantitatively describe the long-term hydrologic dynamics of the TDF; (2) to evaluate its response to major hydrometeorological events (hurricanes); (3) to compare such response with the long-term patterns; and (4) to discuss some forest management implications in relation to extreme climatic events.

2. Materials and methods

2.1. Site description

The long-term study is being conducted at the Biological Station of UNAM located in the Chamela-Cuixmala Biosphere Reserve, 2 km inland from the Pacific coast of Jalisco, Mexico (105°W, 20°N). Five small watersheds (12–28 ha each) were selected as study units (for general features and location of the watersheds, see Martínez-Yrízar et al., this issue). All watersheds are under natural (without human perturbation) conditions and covered with tropical dry forest. Rainfall is highly seasonal and highly variable from year to year (annual range from 340.0 to 1329.0 mm). Mean annual rainfall is 800.4 mm (1983–2015), with 86.8% falling between June to October, and September (214.9 mm) is the wettest month on average. Mean annual temperature is 25.6 °C (1980–2015) with minor variation among years. Monthly mean minimum and maximum temperatures are 16.4 °C (March) and 32.6 °C (August), respectively. As a result of this climatic pattern, the potential evapotranspiration in the region is higher than precipitation during 10 consecutive months of the year, creating a high evapotranspiration demand and a substantial consumption of the available water through ecosystem latent heat fluxes (Maass and Burgos, 2011).

Except for isolated and incipient alluvial valleys and coastal plains, the topography is dominated by hills with mainly convex slopes of 15° to 60° and a range in elevation of 20–180 m (Maass et al., 1988; Cotler et al., 2002). Soils, identified as Entisols according to the Soil Survey Staff (2009), are young, often shallow (0.2–0.6 m depth), poorly structured and with an A and AC horizon (Solís, 1993). They are sandy loams in texture, neutral (pH 6.5), with a bulk density of 1.17 g cm^{-3}, and with low organic matter (2.4%). Phosphate is also low, whereas calcium is abundant (57.2 and 3,495.1 kg ha^{-1}, respectively). Total cation exchange capacity is 8.7 meq (Maass et al., 1988).

The predominant vegetation in the area is the tropical dry forest (Rzedowski,1978) mostly distributed on the hills and slopes. Tropical semi-deciduous forest occurs along the arroyos, riparian associations, coastal strands, mangrove swamps, and brackish lagoons in the low valleys (Lott, 1993). It is a highly diverse ecosystem with > 1000 spp. of vascular plants (Lott and Atkinson, 2002). Total above-ground phytomass in the slopes is 85 Mg ha^{-1} (Martínez-Yrízar et al., 1992). Long-term (1982–2009) average litter production varies among watersheds from 3.5 to 4.9 Mg ha^{-1} y^{-1} (Martínez-Yrízar et al., this issue) and the litter layer from 7.0 to 8.1 Mg ha^{-1} (Patiño, 1990). Mean stem density (dbh > 3.0 cm) is 2750 ha^{-1}, mean basal area is 17.6 m^2 ha^{-1}, and the average canopy height is 7 m. Leaf area index varies from 1.0 m^2 m^{-2} in April to 4.7 m^2 m^{-2} in September (Maass et al., 1995).

During the second half of last century, the tropical dry forest in the region has been subjected to intense transformation. Usually, the forest is burned after clearing with axe and machete. Maize is planted for about two years, and then replaced with grass for grazing (*Panicum maximum* Jacq. and *Cenchrus ciliaris* L.; De Ita, 1983). Soil erosion was measured in experimental plots covered by forest as almost negligible (less than 0.2 Mg ha^{-1} y^{-1}), whereas in the maize and grass fields rates can be as high as 130 Mg ha^{-1} y^{-1} (Maass et al., 1988).

2.2. Rainfall and runoff monitoring

Rainfall monitoring was initiated in 1983 and has been measured continuously using a calibrated Belfort bucket recording rain-gauge, at the Chamela Biological Station located within the 2 km^2 study area. Rainfall depth, duration and intensity values were extracted for each individual precipitation event, with a precision of 0.5 mm. It was considered a different rainfall event when recording stopped for > 2 h.

Standardized Precipitation Index (SPI; McKee et al., 1993) was used to detect intra-annual droughts (canículas). SPI values between 0.99 and −0.99 were considered 'near normal'; values between −1.0 to −1.49 as 'moderately dry', values between −1.5 to −1.99 as 'severely

dry', and values −2.0 or less as 'extremely dry'.

Stream flow was recorded continuously at the bottom of each catchment using H type flumes. A Stevens S-F3-2 water level recorder was used to measure water-level with a precision of 0.5 mm for intervals of 15 min. Since 2012, Solinst water level loggers (model 3001) were installed, with a precision of 0.1 mm for intervals of 2 min. Watershed size was used to calculate runoff depth in mm.

On certain occasions, there were runoff values missing (less than 10% of the whole data set). To calculate monthly or yearly runoff values, the missing values were estimated through regression analysis performed for each watershed using all available runoff values paired with the average runoff values of the rest of the watersheds (as the independent variable). On average, 97% of the variation was explained by these regression equations (mean r^2 = 0.973).

Sediment yield was measured during 11 years (2005–2015) by placing three consecutive stainless steel screens of different mesh size at the river channel to separate the runoff material (branches, leaf-litter and soil particles) at the watershed's outlet. At the end of each hydrological year (June through May), all screens were sampled for trapped sediments, and all the material was removed from the sampling site to obtain yearly measurements.

3. Results

3.1. Rainfall

Average annual precipitation for the 33-y study period (1983–2015) was 800.4 mm (Fig. 1, Also Table 1, in Supplementary Material) with a very high inter-annual variability among years (SD of 273.1 mm; CV of 34.1%). In the wettest year (2015), precipitation (1329 mm) was 3.9 times higher than in the driest year, 2005 (340 mm), a difference of 989 mm.

Intra-annual rainfall was also highly variable (Fig. 2A). The wettest month (September) averaged 214.9 mm y^{-1}, while the driest (April) only 0.3 mm. (Table 1 in Supplementary Material). June to October was the wettest period (with 87% of total annual precipitation). September was particularly variable (7.0 and 777.0 mm, in 1996 and 1998, respectively) and January as well (CV = 389%).

There was little variation in the number of rainfall events between years (53; CV 19%). Nearly 80% of the events were < 20 mm. These frequent, but small events, contributed 28% to total rainfall (Fig. 3A). In contrast, 5.5% of the rainfall events were > 50 mm, delivering 42% of total precipitation to the area.

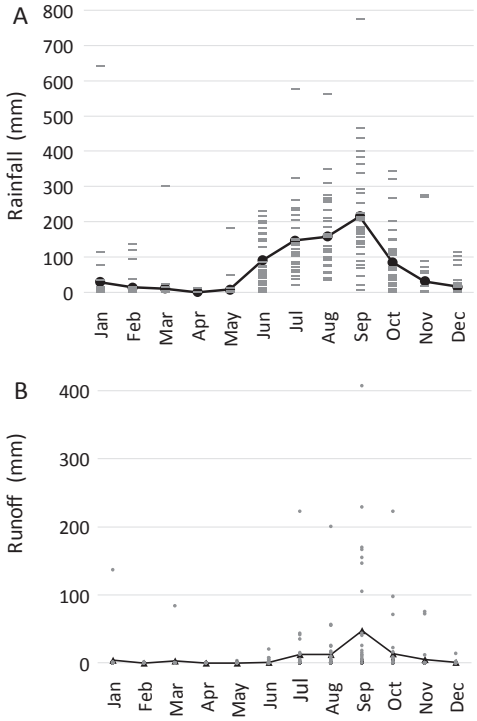

Fig. 2. A) Monthly rainfall values and B) monthly runoff values for the period 1983–2015 in Chamela, Jalisco, Mexico.

There were a total of 126 "large storms" (> 50 mm, and up to 235 mm), with an average of 4 "large storms" per year. Sixty percent of the large events (> 100 mm) occurred in September.

The rainfall in the Chamela region is highly concentrated in the year. Consequently, there are lengthy periods with little or no rain. During the wet season (with several events within a week), the average length of the rainless period is one week (6.9 days); however, there were periods of up to eight months (247 days) without rain. On average, every year had at least one rainless period of > 90 days. The time elapsed between rainfall events depended on their magnitude: small events (1–10 mm) are mostly separated by days or weeks; large storms (> 50 mm) are months and years apart (Fig. 4A).

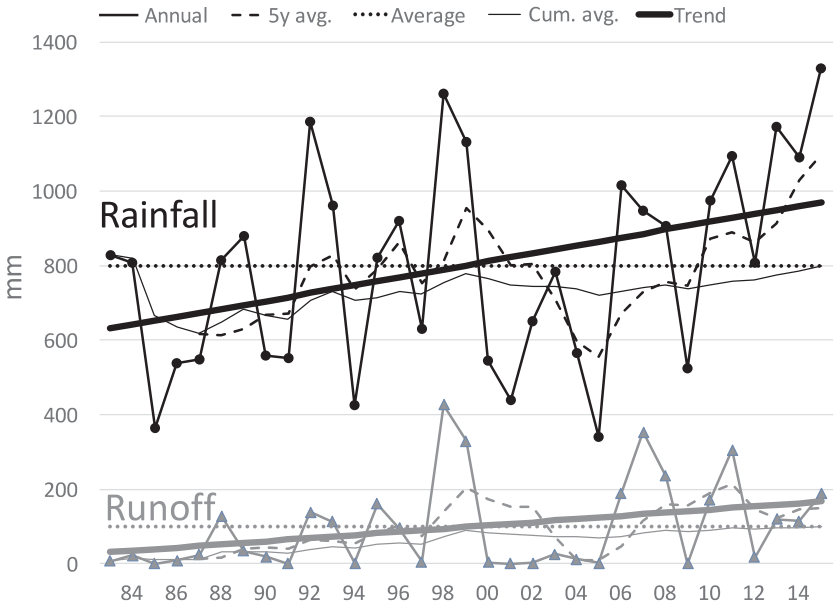

Fig. 1. Long-term (1983–2015) of annual, average, cumulative average, 5-year average and linear historical trend of rainfall (upper dark lines) and runoff (lower light lines) in Chamela, Jalisco, Mexico.

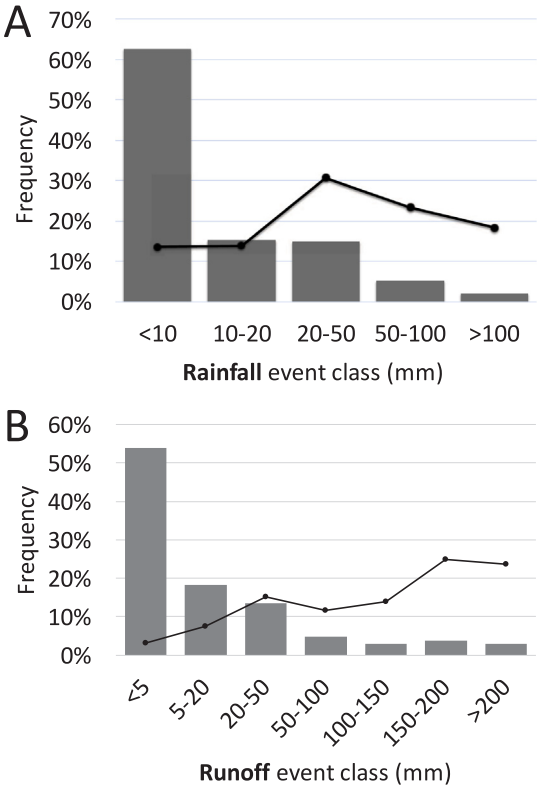

Fig. 3. Frequency distribution of (A) rainfall and (B) runoff events (columns) and relative contribution to the (A) total annual rainfall and (B) total annual runoff (lines) for the period 1983–2015 in Chamela, Jalisco, Mexico.

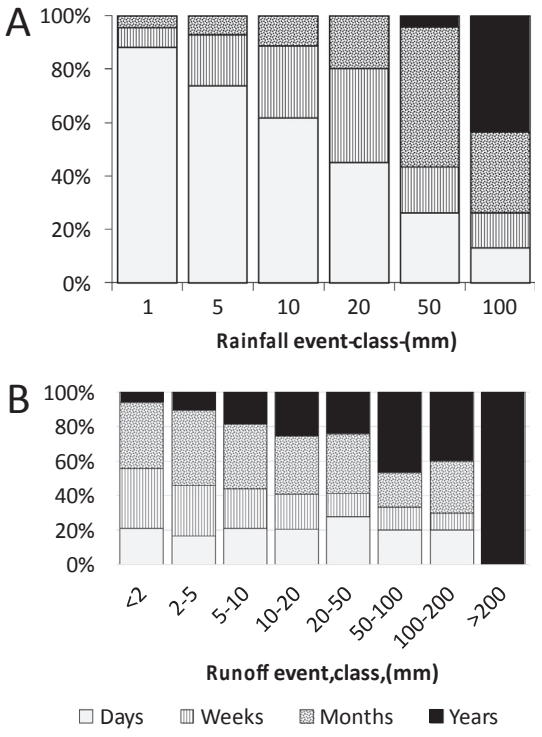

Fig. 4. Frequency distribution of the return period of (A) rainfall events and (B) runoff events for the period 1983–2015 in Chamela, Jalisco, Mexico.

The "beginning of the rainy season" was defined as the date of the first rain of the first week that accumulated > 10 mm after a prolonged (> 60 days) rainless period. Accordingly, the "end of the rainy season" (or "beginning of the dry season") was defined as the last day of the last week that accumulated > 10 mm of rainfall prior to a prolonged rainless period (> 60 days). The average onset and end of the rainy season in Chamela are June 13 and November 8, respectively (Fig. 5). The beginning of the rainy season did not deviate > 23 days from the average, whereas the end of the rainy season deviated almost by three months on average.

The length of the wet season was 4.9 months on average, the rest (7.1 months) being the dry season (40% and 60% of the year, respectively). However, the seasons' length varied highly among years. The rainy season was as short as three months or less (e.g. 1995 and 2007), or as extended as nine months or more (e.g. 2014).

3.2. Runoff

Average annual runoff (considering all 5 watersheds) during the study period (1983–2015) was 99.0 mm (SD of 119.7; Table 2 in Supplementary Material). The annual variation in runoff was much higher than the variation in rainfall (CV of 121% and 34%, respectively). There were significant differences among years, with a maximum annual value of 427.2 mm in 1998 and a minimum of 0.0 mm in 2001 (Fig. 1). Runoff was also highly variable within the year (Fig. 2B). September was, by far, the month with the highest runoff, with an average of 47.5 mm (48% of average annual runoff). As much as 406.9 mm of runoff was recorded in September of 1998, a value that is 8.6 times higher than the historic average for the month (47.5 mm). No runoff has ever been observed in April, and only once in March and in May. The probability of runoff occurrence is less than 10% during the dry season (Nov-May accumulated only 12% of yearly runoff).

The transient nature of the streams in the Chamela region is so marked that the regular condition of the streams is of dryness, with sporadic episodes of running water lasting only a few days after a heavy rainfall event (> 200 mm month^{-1}). In fact, there were more than one order of magnitude fewer runoff events than rainfall events: 3.6 vs 53.1 events y^{-1}, respectively. Also, variation in the number of runoff events among years was much higher than the number of rainfall events: CV of 67% vs 19%, respectively. Some years had up to nine runoff events (2011), whereas in many years, runoff events were absent. As much as 72% of the runoff events were less than 20 mm (Fig. 3B), contributing only 10% of total recorded runoff. In contrast, 63% of the runoff was produced by only 10% of the runoff events of high magnitude (> 100 mm).

There were also long periods with scant or no runoff at all. The average period between runoff events was 100 days (14.3 weeks); however, there was a long period of almost 2 years (656 days) between runoff events (from Sep 13,1991 to Jun 30, 1993). In fact, there were 26 occasions during the study period of 33 years with eight consecutive months between runoff events. The time elapsed between runoff events depended on their magnitude (Fig. 4B): small events (< 20 mm) were separated by months; large runoff events (> 50 mm) by years, and extraordinary events (> 200 mm) by decades.

3.3. Rainfall/runoff relationship

The average annual runoff coefficient (annual runoff/annual rainfall) was 9.8% with high variation among years (CV of 112%; Table 2 in Supplementary Material). In 2001, the annual runoff coefficient was 0.0, whereas in 2007, it reached 37.3%. As expected, there was a significant positive correlation ($r = 0.818$, $p < 0.01$) between the runoff coefficient and annual rainfall. On a yearly basis, it required at least the historic average rainfall (800 mm) to generate a significant (> 25 mm) annual runoff (Fig. 6A), as it happened half of the recorded years. Also, one third of the years did not show > 10 mm of stream flow in the wet season. On a monthly basis, > 200 mm of rainfall were needed to generate at least a 10 mm of runoff (Fig. 6B). This explained why local streams only flow during the rainy season, mainly in September, the

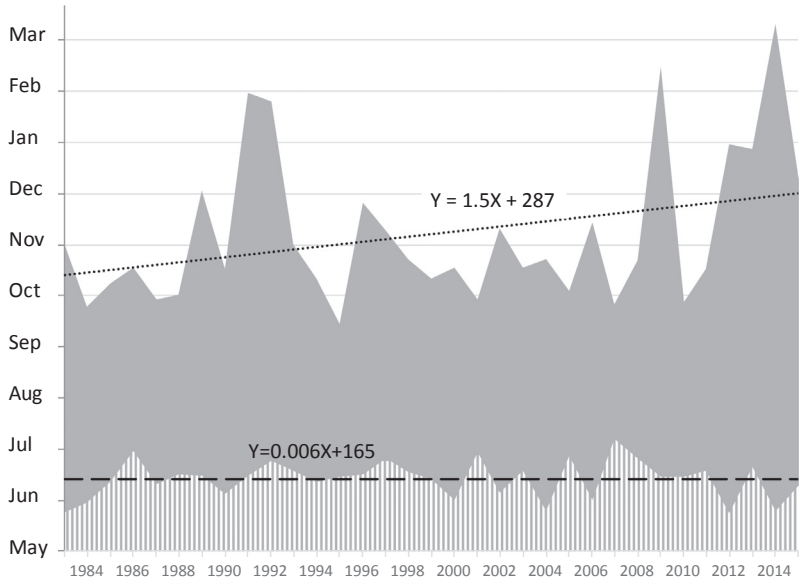

Fig. 5. Long-term (33 years) variation of the day of the beginning (bottom border of the dark area) and the end (top border of the dark area) of the rainy season for the period 1983–2015 in Chamela Jalisco, Mexico. Dashed lines and equations show the trend (linear regression).

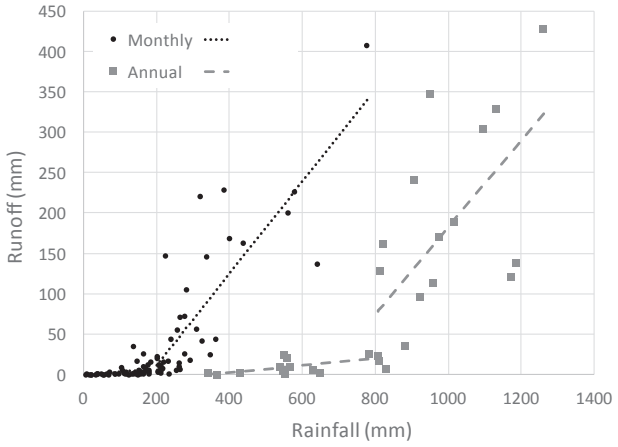

Fig. 6. Long-term (33 years) of monthly (dots) and annual (squares) rainfall vs runoff relationship for the period 1983–2015 in Chamela Jalisco, Mexico.

only month with average rainfall above this threshold (i.e., 214.9 mm; Table 1 in Supplementary Material).

Rainfall was not significantly correlated with total runoff (r = 0.206 with a p = 0.203). However, by adding the previous day rainfall, there was a significant correlation with total event runoff (r = 0. 538 and p < = 0.001). The correlations improved as the rainfall of previous days were added, up to two weeks of antecedent precipitation (r = 0.778). The importance of this previous rainfall was clear on extreme events. For example, a 110 mm rainfall in 24 h on Sep 5th 1984 (with a maximum rainfall intensity of 27 mm h^{-1}), produced only 1.9 mm of runoff (1.7% of the event rainfall), whereas a similar rainfall (105 mm; with a maximum rainfall intensity of 62 mm h^{-1}) in Sep 6th 1988, produced as much as 99.8 mm of runoff (95% of the event rainfall). In the first case, the accumulated rainfall during the three weeks prior to the event was 48 mm, while it was 324 mm in the second case.

3.4. Sediment yield

An average of 205.8 kg ha^{-1} y^{-1} of sediments were transported through runoff fluxes in the watersheds. Annual sediment yield varied two orders of magnitude, between 5.5 and 590.7 kg ha^{-1} y^{-1}, in 2005 and 2007, respectively (Table 3 in Supplementary Material). As expected, there was a significant correlation between annual sediment yield and annual runoff (r = 0.78), which is more than twice the correlation between annual sediment yield and annual rainfall (r = 0.37).

4. Discussion

4.1. Extreme hydrometeorological events and inter-annual variability

One of the longest records of ecological processes in Chamela concerns its water dynamics, allowing the evaluation in comparative terms, the magnitude of the disturbances caused by extreme hydrometeorological events. The most conspicuous characteristics of the hydrologic regime in the Chamela TDF are the strong seasonality and the influence of large cyclonic storms (García-Oliva et al., 1991; García-Oliva et al., 2002). The year 2015, when hurricane Patricia made landfall in the Chamela region, was the wettest year of the 33-yr rainfall record at the Field Station (1329 mm y^{-1}). However, this was not the year with the highest rainfall intensity. In August 2007 Hurricane Dean produced extremely heavy rainfall (236 mm) in less than 24 h (maximum rainfall intensity was 138 mm h^{-1}), while Hurricane Patricia displayed half of that amount during the same period (115 mm; with maximum rainfall intensity of 27 mm h^{-1}). Although both extreme events were caused by a tropical storm, they formed in completely different regions. Hurricane Patricia formed in the South Pacific Ocean, landing directly on the Chamela coast, while Hurricane Dean originated in the Atlantic Ocean, with an impact on the Yucatan Peninsula and the Veracruz coast in the Gulf of Mexico, reaching as far as the Jalisco coast in the Pacific. Hurricane Dean produced a runoff in Chamela of 182.6 mm (Table 2 in Supplementary Material), a record runoff on the 33-years data set, and also one of the highest runoff: rainfall ratios (77.0%). In terms of soil erosion, Dean produced the highest sediment yield in the gauged watersheds, generating as much as 590.7 kg ha^{-1} y^{-1} in 2007 (in comparison with only 103.3 kg ha^{-1} y^{-1} in 2015, year of Patricia; Table 3 in Supplementary Material).

Hurricane activity not only brings a large amount of water to the system, but it is often accompanied with strong winds. The synergistic effect produces an increase in litterfall production during the months hit by the heavy storms (Martínez-Yrízar et al., this issue).

Rainfall is one of the most important factors controlling the structure and functioning of TDF ecosystems; however, it is an exogenous variable no under management control. Predicting rainfall is a major concern among local decision makers and becomes crucial information to farmers who depend on rain-fed systems of production (e.g. subsisting agriculture and pastoral practices; Burgos and Maass, 2004).

This is important since most farmers depend on good rainy seasons. Long-term meteorological records can help them to understand patterns and levels of uncertainty of annual rainfall, assisting in their decision-making process. As reported here, there is very high inherent inter-annual rainfall variability, and the probability of having a dry year (less than the average 800.4 mm y^{-1}) is slightly lower than having a wet year (42% and 57%, respectively). Considering a 20% deviation from the mean as "normal" rainfall (between 640 and 960 mm y^{-1}) the probability of having a "normal", "above normal", and "below normal" rainfall year is very similar: 36, 27 and 36%, respectively. Likewise, the probability of having 20% more rainfall next year, 20% less rainfall or equal (less than 20% deviation) rainfall is very close: 33, 31 and 36%, respectively. Under this scenario, local farmers should plan for wet and dry years instead of always hoping for a wet year. Also, they should consider the possibility of having extreme cases of several dry years in a row, like the period from 2000 to 2005 in which total rainfall was on average 515 mm y^{-1}, or several wet years in a row, like from 2010 to 2015 when rainfall was well above average (1047 mm y^{-1}).

4.2. Length of the rainy season

Native plants and animals are adapted to this highly unpredictable and strongly seasonal hydrologic pattern. For example, most tropical dry forest plants shed their leaves in the dry season as a mechanism to avoid the effects of drought (Holbrook et al., 1995; Martínez-Yrízar, 1995), and soil wetting is the main factor that triggers leaf and bud expansion at the beginning of the growing season (Holbrook et al., 1995) as well as soil phosphorus release (Campo et al., 1998) and nitrogen transformations (Anaya et al., 2007). These processes are coordinated with the rainy season - it usually requires an accumulation of > 10 mm of rainfall within a week after a prolonged dry season to initiate a rapid and synchronized leaf-flush. Also, high fine-root production at the beginning of the rainy season has been reported (Kummerow et al.,1990).

Although early cyclonic storms can accelerate the onset of the rainy season by a few weeks, late cyclonic storms can prolong the rainy season for several months. This variability has a significant impact on forest productivity and overall ecosystem development (Parker, et al., this issue). For example, long-term litterfall data from the Chamela TDF shows that in years with an extended rainy season as in 1991–1992 (1205 mm), litter production (a proxy of primary productivity) was on average 23% higher than during 1987–1988 with a short and well-below average precipitation (529 mm) (Martínez-Yrízar et al., in prep.).

As mentioned, the rainy season starts after a prolonged drought period and on a leafless canopy. Therefore, the first rains of the season are important to maintain the massive leaf production process for most species of vascular plant in the dry forest ecosystem (Solís-Magallanes and Bullock, 1990). However, the initial conditions of the rainy season are highly variable from year to year (Fig. 7). While the average rainfall on the first day of the season is 21 mm, it can be as low as 0.5 mm, or as high as 180 mm (CV 162%). The accumulated rainfall during the first week of the season is twice absolutely (55.3 mm in average) but half as variable (CV 81%). Similarly, the accumulated rainfall of the two first weeks and the first 4.5 weeks (one month) since the beginning of the wet season, reached 108.5 and 181.2 mm, respectively, with less than 70% coefficient of variation in both cases. Although native plants are adapted to this high variability at the beginning of the rainy season, it may be a challenge to many introduced species, and it is often a cause of crop failure for local farmers. Therefore, it is wise to wait until at least one week after the onset of the rainy season for any management activity requiring rain water (e.g. crop seeding or seedling planting on a reforestation program).

4.3. Soil erosion

Cyclonic storms bring large amounts of water in a short period, generating high erosive activity (Maass et al., 1988; García-Oliva et al., 1995). Several rainfall events > 50 mm occurred every year in the study area, and up to 10 of those storms can occur in a single year (as in 2015). Also, storms > 100 mm were present in 73% of the 33-y period. The greatest storm event (236 mm) was recorded in August 23, 2007, with a maximum intensity of 138 mm h^{-1}. There was one month (September 1999) with six consecutive days with > 50 mm. Also between August 30th and September 8th, 2010, there was a record of 10 consecutive rainy days, accumulating a total of 322 mm, with high rainfall in four of those days (with max intensities of 20.4; 28.3; 27.3 and 25.3 mm h^{-1}).

Under undisturbed conditions, the forest canopy and the surface litter protect the soil from the physical impact of these high intensity rains (Maass et al., 1988). However, since soils are very shallow and sandy (Cotler et al., 2002), with limited soil water holding capacity, the watersheds are highly responsive to these cyclonic storms, generating a quick runoff (Cervantes et al.,1988; Cervantes, 1988). Also, when the first rains of the season arrive, the forest is almost completely leafless. Starting with a leaf area index of 1 $m^2 m^{-2}$ at the onset of the rainy season, it takes 2–3 months for the forest to reach its full canopy, up to 5 $m^2 m^{-2}$ (Maass et al., 1995). However, the accumulation of leaf-litter on the forest floor reaches its peak precisely just before the onset of the rainy season (Martínez Yrízar and Sarukhán, 1993). Nevertheless, when the forest is cut and fire is used as a management tool, the protecting litter layer disappears, exposing the soil to the impact of rainfall drops and inducing a strong land degradation process (Maass et al., 1988; Bruijnzeel, 1990; Maass, 1995). Since 2/3 of the years included a highly erosive storm (> 50 mm d^{-1}) within the first 30 days of the rainy season, the probability of a having such storms is 66%. This condition is exacerbated by the relatively steep slopes of the hilly landscape of the area and the erodible nature of the soil (Maass et al., 1995). That is why it is important to maintain a protective soil cover (such as through mulching) during any forest management activity, which involves the removal of the original leaf-litter deposited on the forest floor (Maass et al., 1988).

A closer analysis shows that in eight years, the beginning of the rainy season was accompanied with storms > 100 mm. Extreme rainfall events over a deforested and bare soil usually generate high soil erosion, which not only removes critical soil nutrients for plants, but also the seed bank required for the forest recovery process (Han et al., 2011). This adds difficulties to the interpretation of forest "chrono-sequence" studies in the area, since there is a strong "founder effect" related to the year the original forest was transformed. For example, a chrono-sequence of an abandoned successional field initially deforested (clear-cut) in 2002 would probably follow a different recovery process than another plot with exactly the same management treatment, but deforested a year later (2003), since the accumulated rainfall at the beginning of the rainy season (first month) was 46 mm in 2002, and 298 mm in 2003.

4.4. ENSO and recurrent drought periods

There is a clear influence of the "El Niño" - Southern Oscillation (ENSO) phenomenon on the study area. During the 33 years of the study period, there were 9 ENSO events (Trenberth, 2013; NOAA, 2017). Average rainfall in Chamela during "El Niño" years are significantly lower, particularly during the wet season (Fig. 8). However, the dry season months and those in the transition between the wet and the dry seasons (November–February) tend to be slightly wetter than the average rainfall for those periods. In contrast, average rainfall during the "La Niña" events (a cold phase of ENSO) shows a statistical significantly higher precipitation during the wet months (June–October), and lower precipitation during the transition and dry months. The highest intense storm registered in Chamela was precisely on "La Niña" year of 2007.

Although excess of water is a clear expression of an extreme

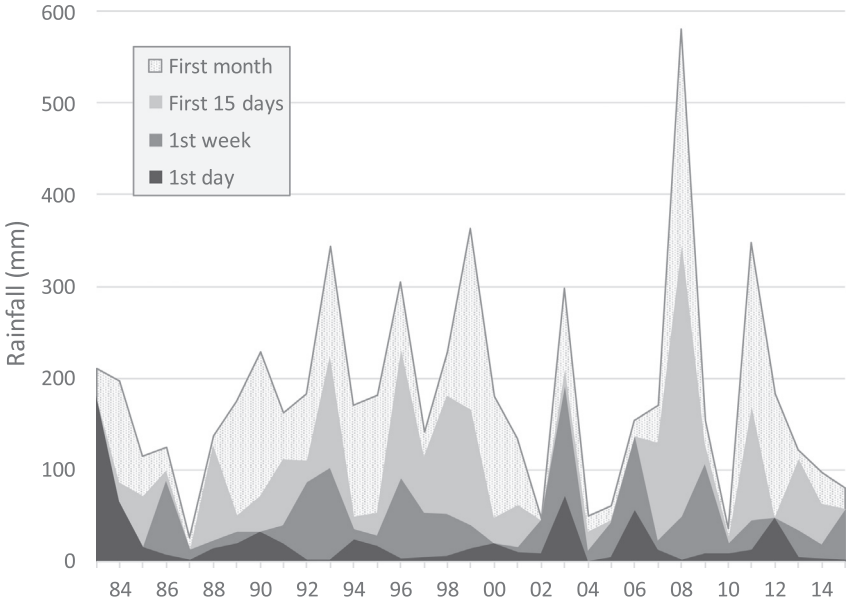

Fig. 7. Long-term (33 years) cumulative rainfall (mm) during the onset of the rainy season for the period 1983–2015 in Chamela, Jalisco, Mexico.

hydrometeorological event, lack of water can be even a more significant stressor to the ecosystem. One way to evaluate the occurrence of a drought is to calculate the accumulated deviation from the historical mean. The long-term hydrological record shows the occurrence of three severe drought episodes in the Chamela region (Fig. 9A): (1) at the beginning of the study (1985–1987), with only 366 mm y^{-1} in 1985, and a 3-year annual rainfall average as low as 484.2 mm y^{-1}; (2) a shorter 2-year drought (1990–1991); and (3) the strongest 6-year drought (2000–2005), with a mean annual rainfall of 554 mm y^{-1} and in the driest year (2005), with only 340 mm y^{-1} (just 42% of the historic average and 23% of the maximum recorded). The accumulated deviation from the historical mean reached minus 1500 mm. Using the same procedure, but at a finer scale (monthly values) the analysis shows recurrent negative deviations from the mean (Fig. 9B), with negative cumulative deviations above 600 mm, particularly during the strongest drought period (2000–2005), in which the deficit lasted for almost two consecutive years (22 months) reaching a peak accumulated deficit of 854.3 mm. These recurrent drought and wet periods for several years are linked with ENSO phenomena, as the arrows in Fig. 9A indicate. Lowest and highest litter production rates are also well associated to these dry and wet years (Martínez Yrízar et al., this issue).

Another hydrometeorological characteristic of this tropical dry forest ecosystem is the occurrence of a short dry period during the wet season, known as “canícula”, occurring almost every year (27 out of 33 years), but not always in the same month; it occurs in August (Fig. 10A) in 41% of the years, and in July (Fig. 10B) in 33% of the years. The average reduction in rainfall during August’s canícula is 49.7% of the previous month, but in July it is much stronger, with a 240% reduction, on average. The analysis using a standardized precipitation index (SPI; McKee et al., 1993) showed that most of July’s canículas were ‘near normal’. However, some extreme cases like 2000 and 2014 were observed, with especially long canícula with less than 40% of average historic rainfall, and the 1996 a double canícula (July and September; Fig. 10A).

The results show that a canícula event can be present in both hot (El Niño) or cold (La Niña) phases. However, hot phases produce fewer

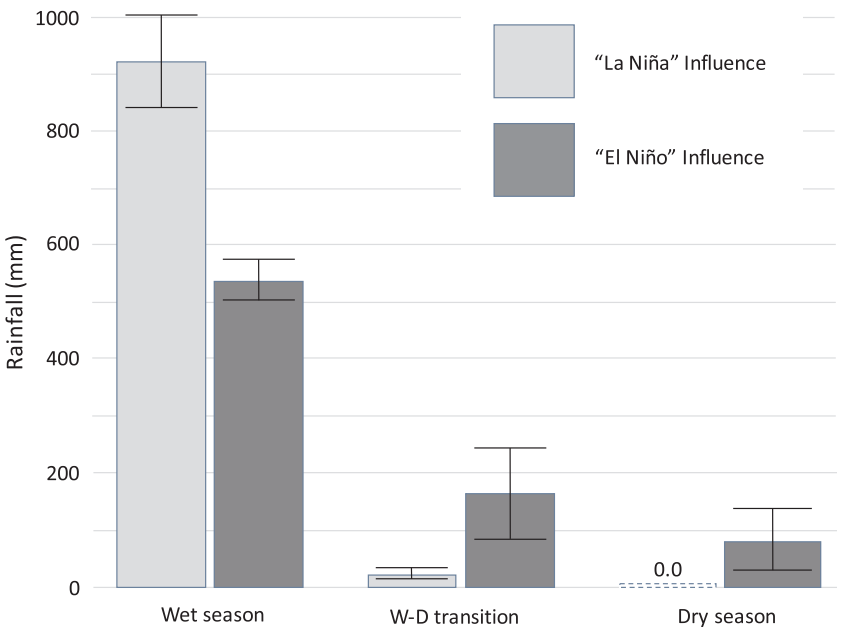

Fig. 8. Average rainfall (mm; +/− one standard error) under the influence of “El Niño” and “La Niña” - Southern Oscillation (ENSO), during the wet months (June–October); the dry months (March–May) and the Wet Dry transition (November–February) for the period 1983–2015 in Chamela, Jalisco, Mexico.

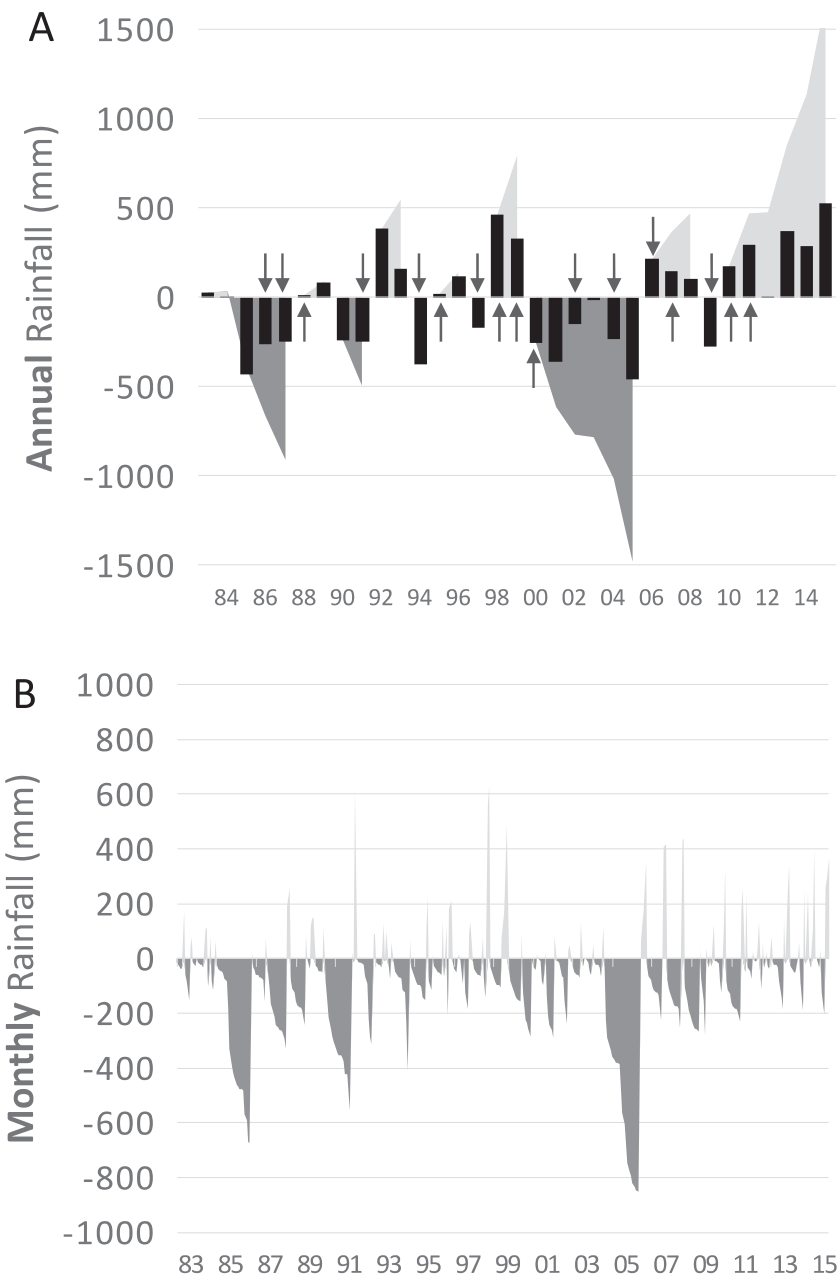

Fig. 9. Long-term (33 years) deviation from the historical rainfall mean (bars in A; mm y^{-1}) and cumulative deviation (grey areas in A and B; mm) for the period 1983–2015 in Chamela, Jalisco, Mexico. (A) Annual rainfall values and (B) Monthly rainfall values. Down arrows in A indicate ENSO years; up arrows indicate "La Niña" phase.

canícula events on both months, compared with the cold and transition phase, that produce most of the canícula events.

Native species are adapted to these canículas; however, a drought in the middle of the growing season can be a serious problem for local farmers, particularly subsistence farmers who rely on rain-fed agriculture. The results suggest that the 44% and 45% July and August's canículas have important consequences for water management. This includes not only for local subsistence farming, but for any forest management program that requires a continuous and secure source of water (particularly during reforestation programs).

5. Summary and final remarks

Because water is the most limiting factor for TDF productivity, understanding its dynamics is crucial for ecosystem management and conservation. Assembling long-term data provides the only way to fully understand ecological processes, especially under highly variable climatic conditions. It can place current phenomena in a historical perspective. It is clear from the analysis here, that uncertainty is the norm - its recognition and its incorporation into decision-making processes is essential through an adaptive management process. Despite these uncertainties, there are some specific hydrological patterns useful to take into consideration for TDF management. For example: the remarkably constant onset of the rainy season; the highly variable rainfall pattern during the first weeks of the season; the high probability of an erosive storm at the beginning of the season; the similarity in the chances of having 20% higher, the same or 20% lower rainfall the following year; the high probability of occurrence of an intra-seasonal drought (canícula) in August than in July; the near almost certainty that September will be wet, and that 87% of the yearly rain will fall in just five months; and the clear pattern of less than the average annual rainfall during "El Niño" years, and above the average during the "La Niña" years.

The Chamela region is a coastal area on the Pacific Ocean, and tropical storms are an important exogenous source of water deposition and disturbance to the area. However, and contrary to common sense,

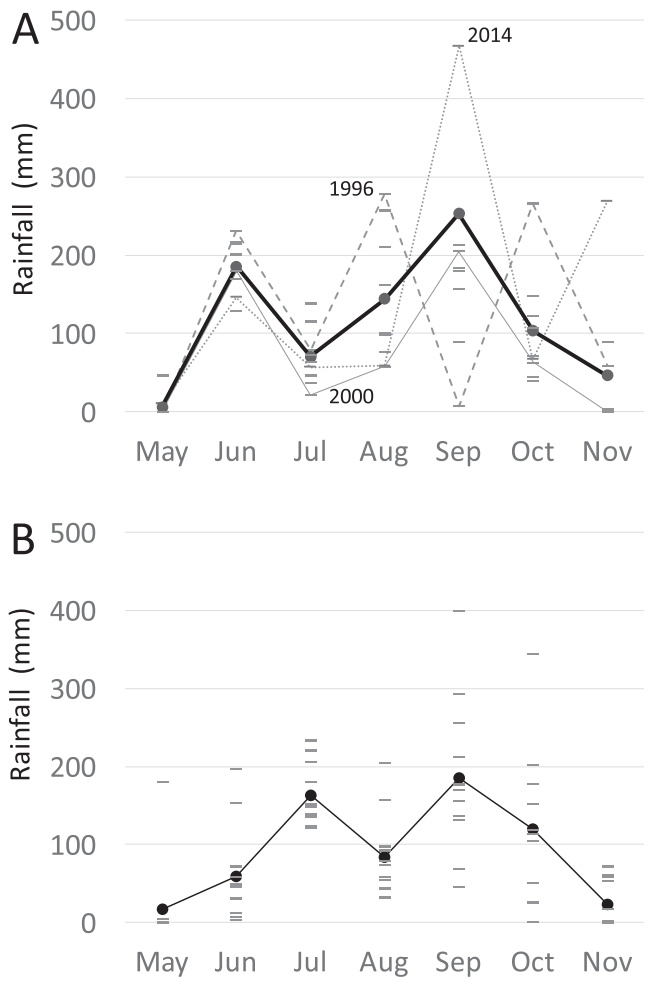

Fig. 10. Monthly rainfall average (solid lines; mm month^{-1}) and monthly rainfall values (marks) during (A) July's canícula years (short intra-annual drought), and (B) August's canícula years for the period 1983–2015 in Chamela, Jalisco, Mexico.

the strongest historical impact in terms of rainfall intensity, runoff and soil erosion was due to a hurricane, originated and developed in the Atlantic Ocean ("Dean" in 2007). Managers should be aware of such distant threats and prepare for such contingencies.

As a result of this tropical storm influence in the region, highly erosive storms are frequent in the study area and can occur at any time, even during the dry season. The presence of well-preserved forest in the Chamela region is a clear sign of its resistance and resilience capacity to cope with this highly erratic climate. However, the common occurrence of highly erosive storms makes TDF particularly vulnerable to land transformation. Protecting the soil from these erosive rainfall forces, by maintaining a leaf-litter layer on the forest floor, is a simple and efficient management tool for forest soil conservation (Maass et al., 1988).

Excess of water has been identified as a major hydrometeorological risk, particularly when a high intensity storm falls on already wet soils (Maass et al., 1988). Shallow and sandy soils are a common feature in the Chamela region, thus high intensity storms can produce flashy storm runoff behavior. This, combined with the dominant hilly landscape (Cotler et al., 2002), facilitates water redistribution with strong synergistic effects. Monitoring rainfall is an efficient management tool to estimate, on site and on real time, the antecedent soil moisture, which allows forecasting flood and soil erosion risk.

The long-term analysis shows that the average runoff/rainfall coefficient is less than 9.8%, which means that only a very small fraction of the total annual rainfall (less than 10%) contributes to local groundwater recharge (the rest leaves the ecosystem through evapotranspiration process (Vose and Maass 1999; Burgos, 1999). Therefore, it requires at least 800 mm of rainfall in a year to produce significant runoff, and half of the time it does not reach that amount. On a monthly basis, the runoff/rainfall proportion is even lower (5%) and it requires a rainfall > 200 mm month^{-1} to generate runoff. Only September has a rainfall average higher than that magnitude. Therefore, local groundwater recharge only occurs either with highly intense storms or when storm occur in relatively high antecedent soil wetness conditions. When these storms fall on a well-preserved forest, base and subsurface flows tend to dominate the runoff processes, which contributes to groundwater recharge (Muñoz-Villers et al., 2016). However, the same highly intense storms falling under deforested conditions tend to promote overland runoff fluxes, soil erosion, and significant lower groundwater recharge and floods (Muñoz-Villers and McDonnell, 2013).

TDF species are well adapted to the climatic uncertainties generated by the rainfall variability described in detail here. Therefore, TDF species are an important genetic pool to cope with the extreme meteorological events forecasted by climate change scenarios. However, it is also important to keep in mind that the regulating processes maintaining ecosystem resilience capacity not only depend on a few species, but on a full and well preserved ecosystem. Therefore, maintaining ecosystem integrity is the best way to protect this important genetic pool.

Finally, although long-term ecological monitoring represents a costly effort with a tremendous research commitment, such research supplies critical information, not only to understand regional and global scale processes, but also to help local settlers with their management decisions (Hughes et al., 2017). However, this last process of transferring scientific knowledge to local communities has been difficult (Vaughan et al., 2007), and new epistemic approaches are emerging to cope with this problem (Fischer et al., 2015). This is reflected in the recent process of transitioning from a long-term ecological research (LTER) perspective, to a more long-term social-ecological research (LTSER) viewpoint (Collins et al., 2011). Furthermore, in recognition of the need to involve local communities to participate in the research and monitoring processes, it has been proposed to include a transdisciplinary approach into a more long-term socioecosystem research LTSESR (Maass and Equihua, 2015; Maass, 2017) framework.

Acknowledgements

To Atzimba López, Lyliana Rentería, Humberto Ferreira and Alberto Valencia who helped with manuscript preparation. We thank two anonymous reviewers and Juan Carlos Álvarez-Yépiz for their comments to improve the manuscript. We also thank Ma. Eugenia González for supplying barometric data to calibrate water level sensors. The Chamela Long-Term Ecological Research Project (Chamela Mex-LTER) has been the effort of many people during more than 3 decades. We would like to acknowledge Carl Jordan from University of Georgia for helping in the initial promotion and design of the project with an LTER philosophy and Wayne Swank and Jim Vose from Coweeta Hydrologic Laboratory for their scientific advice during the early years of the project. To Estación de Biología de Chamela (EBCH-IB-UNAM) for its long-term support and commitment, particularly to Luis Cervantes, Alfredo Pérez Jiménez and Arturo Solís Magallanes for their help in establishing the monitoring infrastructure in the field and to Enriquena Bustamante for logistic support. The long-term support from several funding agencies is acknowledge, particularly from the Universidad Nancional Autónoma de México (UNAM) and the Consejo Nacional de Ciencia y Tecnología (CONACYT). Currently, the project has a support from CONACYT Project No. 179045 and UNAM-PAPIIT Project No. IN209117; AMY thanks PASPA-DGAPA, UNAM, for a sabbatical fellowship (2016-2017) at the University of Arizona.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2017.09.040.

References

Anaya, C.A., García-Oliva, F., Jaramillo, V.J., 2007. Rainfall and labile carbon availability control litter nitrogen dynamics in a tropical dry forest. Oecologia 150, 602–610.

Álvarez-Yépiz, J.C.,Martínez-Yrízar, A., 2015. Huracanes, sequías y heladas: eventos climáticos extremos en México. Oikos = 14 December 2015 14:40. [http://web.ecologia.unam.mx/oikos3.0/index.php/oikos-historico/numeros-anteriores/165-eventos-climaticos-extremos-en-ecosistemas?tmpl = component&print = 1&page =].

Bruijnzeel, L.A., 1990. Hydrology of moist tropical forest and effects of conversion: a state of knowledge review. Free University, Amsterdam, UNESCO International Hydrological Programme, pp. 224.

Bullock, S., Medina, E., Mooney, H. (Eds.), 1995. Seasonally Dry Tropical Forests. Cambridge University Press, USA.

Burgos, A. 1999. Dinámica Hidrológica del bosque tropical seco en Chamela, Jalisco. Master Thesis. Facultad de Ciencias, UNAM-Morelia, Mexico.

Campo, J., Jaramillo, V., Maass, J.M., 1998. Pulses of soil phosphorus availability in a Mexican tropical dry forest: effects of seasonality and level of wetting. Oecologia 115, 167–172.

Ceballos, G., García, A., 1995. Conserving Neotropical biodiversity: the role of dry forest in western mexico. Conservat. Biol. 9 (6), 1349–1353.

Cervantes, L., 1988. Intercepción de lluvia por el dosel en una comunidad tropical. Ingeniería Hidráulica en México. Segunda época, Vol. III (2), 38-43.

Cervantes, L., Maass, J.M., Domínguez, R., 1988. Relación lluvia escurrimiento en un sistema pequeño de cuencas de selva baja caducifolia. Ingeniería Hidráulica en México. Segunda Época Vol. III (1), 30–42.

Chapin III, T.S., Matson, P.A., Mooney, H.A., 2002. Principles of Terrestrial Ecosystem Ecology. Springer, New York.

Cotler, H., Durán, E., Siebe, C., 2002. Caracterización morfo-edafológica y calidad de sitio de un bosque tropical caducifolio. In: Noguera, F., Vega, J.H., Quesada, M., García-Aldrete, A. (Eds.), Historia Natural de Chamela. Instituto de Biología, UNAM, México, pp. 17–79.

Collins, S.L., Carpenter, S.R., Swinton, S.M., Orenstein, D.E., Childers, D.L., Gragson, T.L., Grimm, N.B., Grove, J.M., Harlan, S.L., Kaye, J.P., Knapp, A.K., Kofinas, G.P., Magnuson, J.J., McDowell, W.H., Melack, J.M., Ogden, L.A., Robertson, G.P., Smith, M.D., Whitmer, A.C., 2011. An integrated conceptual framework for long-term social–ecological research. Front. Ecol. Environ. 9, 351–357. http://dx.doi.org/10.1890/100068.

De Ita, C., 1983. Patrones de producción agrícola en un ecosistema tropical en la costa de Jalisco. Tesis de Licenciatura, Facultad de Ciencias, Universidad Nacional Autónoma de México, México, pp. 183.

Dirzo, R., Young, H., Mooney, H.A., Ceballos, G. (Eds.), 2011. Seasonally Dry Tropical Forests: Ecology and Conservation. Island Press, USA.

Farrick, K.K., 2014. Runoff Generation in a Tropical Dry Forest Watershed: processes, patterns and connectivity. Electronic Thesis and Dissertation Repository. Paper 2523. Western University.

Fischer, J., Gardner, T.A., Bennett, E.M., Balvanera, P., Biggs, R., Carpenter, S., Daw, T., Folke, C., Hill, R., Hughes, T., Luthe, T., Maass, M., Meacham, M., Norström, A.V., Peterson, G., Queiroz, C., Seppelt, R., Spierenburg, M., Tenhunen, J., 2015. Advancing sustainability through mainstreaming a social-ecological systems perspective. Current Opinion in Environmental Sustainability (COSUST) 1 (14),144–149. http://[http://dx.doi.org/10.1016/j.cosust.2015.06.002] ISSN 1877–3435.

García-Oliva, F., Camou, A., Maass, J.M., 2002. El clima de la Región Central de la costa del Pacífico Mexicano. In: Noguera, F., Vega, J.H., Quesada, M., García-Aldrete, A. (Eds.), Historia Natural de Chamela. UNAM, Instituto de Biología, pp. 3–10.

García-Oliva, F., Ezcurra, E., Galicia, L., 1991. Pattern of rainfall distribution in the central Pacific coast of Mexico. Geografiska Annaler 73 A (3–4),179–186.

García-Oliva, F., Maass, J.M., Galicia, L., 1995. Rainstorm analysis and rainfall erosivity of a seasonal tropical region with a strong cyclonic influence in the Pacific coast of Mexico. J. Appl. Meteorol. 34, 2491–2498.

Han, L., Jiao, J., Jia, Y., Wang, N., Lei, D., Li, L., 2011. Seed removal on loess slopes in relation to runoff and sediment yield. Catena 85, 12–21. http://dx.doi.org/10.1016/j.catena.2010.11.007.

Held, I.M., Soden, B.J., 2006. Robust Responses of the Hydrological Cycle to Global Warming. J. Clim. 19, 5686–5699.

Holbrook, N.M., Whitbeck, J.L., Mooney, H.A., 1995. Drought responses of Neotropical dry forest trees. In: Bullock, S., Medina, E., Mooney, H. (Eds.), Seasonally Dry Tropical Forests. Cambridge University Press, USA, pp. 243–276.

Hughes, B.B., Beas-Luna, R., Barner, A.K., Brewitt, K., Brumbaugh, D.R., Cerny-Chipman, E.B., Close, S.L., Coblentz, K.E., De Nesnera, K.L., Drobnitch, S.T., Figurski, J.D., Focht, B., Friedman, M., Freiwald, J., Heady, K.K., Heady, W.N., Hettinger, A., Johnson, A., Karr, K.A., Mahoney, B., Moritsch, M.M., Osterback, A.-M.K., Reimer, J., Robinson, J., Rohrer, T., Rose, J.M., Sabal, M., Segui, L.M., Shen, C., Sullivan, J., Zuercher, R., Raimondi, P.T., Menge, B.A., Grorud-Colvert, K., Novak, M., Carr, M.H., 2017. Long-term studies contribute disproportionately to ecology and policy. Bioscience 67, 271–281.

INEGI, 2005. Conjunto de datos vectoriales de Uso de Suelo y Vegetación: escala 1:250,000. Serie III. Instituto Nacional de Estadística y Geografía e Informática, México.

INEGI 2013. Conjunto de datos vectoriales de Uso de Suelo y Vegetación, Escala 1:250, 000. Serie V. Instituto Nacional de Estadística y Geografía. México.

IPCC. 2014. Climate Change 2014 Synthesis Report Summary for Policymakers, [https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf].

Janzen, D.H., 1986. Tropical dry forest: the most endangered major tropical ecosystem. In: Wilson, E.O. (Ed.), Biodiversity. National Academy Press, USA, pp. 130–137.

Knutson, T.R., Sirutis, J.J., Zhao, M., Tuleya, R.E., Bender, M., Vecchi, G.A., Villarini, G., Chavas, D., 2015. Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. J. Clim. 28 (18), 7203–7223. http://dx.doi.org/10.1175/JCLI-D-15-0129.1.

Kummerow, J., Castellanos, J., Maass, J.M., Larigauderie, M., 1990. Production of fine roots and the seasonality of their growth in a Mexican deciduous dry forest. Vegetatio 90, 73–80.

Lott, E.J., 1993. Annotated checklist of the vascular flora of the Chamela bay region, Jalisco, Mexico. Occasional Papers of the California Academy of Sciences No. 148, 60 pp.

Lott, E., Atkinson, D., 2002. Biodiversidad y fitogeografía de Chamela-Cuixmala, Jalisco. In: Noguera, F.A., Vega-Rivera, J.H., García-Aldrete, A.N., Quesada-Avendaño, M. (Eds.), Historia natural de Chamela. Instituto de Biología, UNAM, México, pp. 17–79.

Maass, J.M., 1995. Conversion of tropical dry forest to pasture and agriculture. In: Bullock, S., Medina, E., Mooney, H. (Eds.), Seasonally Dry Tropical Forests. Cambridge University Press, USA, pp. 399–422.

Maass, M., 2017. Integrating food-water-energy research through a socio-ecosystem approach. Front. Environ. Sci. 5, 48. http://dx.doi.org/10.3389/fenvs.2017.00048.

Maass, J.M., Jordan, C., Sarukhán, J., 1988. Soil Erosion and nutrient losses in seasonal tropical agroecosystems under various management techniques. J. Appl. Ecol. 25 (2), 595–607.

Maass, J.M., Vose, J.M., Swank, W.T., Martínez-Yrízar, A., 1995. Seasonal changes of leaf area index (LAI) on a tropical deciduous forest in west mexico. For. Ecol. Manage. 74, 171–180.

Maass, J., Balvanera, P., Castillo, A., Daily, G.C., Mooney, H.A., Ehrlich, P., Quesada, M., Miranda, A., Jaramillo, V.J., García-Oliva, F., Martínez-Yrízar, A., Cotler, H., López-Blanco, J., Pérez-Jiménez, A., Búrquez, A., Tinoco, C., Ceballos, G., Barraza, L., Ayala, R., Sarukhán, J., 2005. Ecosystem services of tropical dry forests: insights from long-term ecological and social research on the Pacific Coast of Mexico. Ecology and Society 10 (1), 17. [online] URL: http://www.ecologyandsociety.org/vol10/iss1/art17/.

Maass, J.M., Jaramillo, V., Martínez-Yrízar, A., García-Oliva, F., Pérez-Jiménez, A., Sarukhán, J., 2002. Aspectos funcionales del ecosistema de selva baja caducifolia en Chamela, Jalisco. In: Noguera, F., Vega, J.H., Quesada, M., García-Aldrete, A. (Eds.), Historia Natural de Chamela. Instituto de Biología, UNAM, México, pp. 525–542.

Maass, J.M., Burgos, A., 2011. Water Dynamics at the Ecosystem Level in Tropical Dry Forests. In: Dirzo, R., Young, H., Mooney, H.A., Ceballos, G. (Eds.), Seasonally Dry Tropical Forests: Ecology and Conservation. Island Press, USA, pp. 141–156.

Maass, M., Equihua, M., 2015. Earth Stewardship, Socioecosystems, the Need for a Transdisciplinary Approach and the Role of the International Long Term Ecological Research Network (ILTER). In: Rozzi, R., Chapin, F.S., Callicott, J.B., Pickett, S.T.A., Power, M.E., Armesto, J.J., May, R.H. (Eds.), Earth Stewardship: Linking ecology and ethics in theory and practice. Springer, Dordrecht, Netherlands, pp. 217–233.

Miles, L., Newton, A.C., DeFries, R.S., Ravilious, C., May, I., Blyth, S., Kapos, V., Gordon, J.E., 2006. A global overview of the conservation status of tropical dry forests. J. Biogeogr. 33, 491–505.

Martínez-Yrízar, A., 1995. Biomass distribution and primary productivity of tropical dry forests. In: Bullock, S., Medina, E., Mooney, H. (Eds.), Seasonally Dry Tropical Forests. Cambridge University Press, USA, pp. 326–345.

Martínez-Yrízar, A., Sarukhán, J., Pérez-Jiménez, A., Rincón, E., Maass, J.M., Solís-Magallanes, A., Cervantes, L., 1992. Aboveground living phytomass of a tropical deciduous forest in Mexico. J. Trop. Ecol. 8, 87–96.

McKee, T.B., Doesken, N.J. and Kelist, J. 1993. The relationship of drought frequency and duration to time scale. In: Proceedings of the Eighth Conference on Applied Climatology, Anaheim, California, 17–22 January 1993. Boston, American Meteorological Society, 179–184.

Muñoz-Villers, L.E., Geissert, D.R., Holwerda, F., McDonnell, J.J., 2016. Factors influencing stream base flow transit times in tropical montane watersheds. Hydrology Earth Syst. Sci. 20, 1621–1635.

Muñoz-Villers, L.E., McDonnell, J.J., 2013. Land use change effects on runoff generation in a humid tropical montane cloud forest region. Hydrol. Earth Syst. Sci. 17, 3543–3560.

Murphy, P.G., Lugo, A.E., 1986. Ecology of tropical dry forest. Annu. Rev. Ecol. Syst. 17, 67–88.

NOAA (2017). National Wather Service. Climate Prediction Center. Cold and Warm Episodes by Season. Online [http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml].

Patiño, M.C., 1990. Variación espacial y temporal de la capa de hojarasca (Mantillo) en una selva baja caducifolia en Chamela. Tesis de Licenciatura, Facultad de Ciencias, Universidad Nacional Autónoma de México, Jal. México, pp. 78.

Rzedowski, J., 1978. La vegetación de México. Limusa, México, pp. 432.

Sarukhán, J., Maass, J.M., 1990. Bases ecológicas para un manejo sostenido de los ecosistemas: el sistema de cuencas hidrológicas. In: In: Leff, E. (Ed.), Medio ambiente y desarrollo en México Vol. I. UNAM (CIIH)-Porrúa, México, pp. 81–114.

Soil Survey Staff. 2009. Soil survey field and laboratory methods manual. Soil Surv. Invest. Rep. 51, ver. 1.0. R. Burt (ed.) USDA, NRCS.

Solís, E., 1993. Características físico-químicas de un suelo en un ecosistema tropical estacional. Facultad de Ciencias, Universidad Nacional Autónoma de México, Tesis de Licenciatura, pp. 91.

Solís-Magallanes, A., Bullock, S.H., 1990. Phenology of canopy trees of a tropical deciduous forest in mexico. Biotropica 22 (1), 22–35.

Taber, A., Navarro, G., Arribas, M.A., 1997. A new park in the Bolivian Gran Chaco – an advance in tropical dry forest conservation and community-based management. Oryx 31 (3), 189–198.

Toledo, V., 1991. Bio economic cost of transforming tropical forests to pasture in Latin America. In: Downing, T., Hecht, S., Pearson, H. (Eds.), Development or destruction? The conversion of tropical forest to pasture in Latin America. Westview Press, New York, USA.

Trejo, I., 1998. Distribución y diversidad de selvas bajas de México: relaciones con el clima y el suelo. Tesis de Doctorado, Facultad de Ciencias, UNAM, Mexico.

Trejo, I., Dirzo, R., 2002. Floristic diversity of Mexican seasonally dry tropical forests. Biodivers. Conserv. 11, 2063. http://dx.doi.org/10.1023/A:1020876316013.

Trenberth, K.E., 2013. El Niño Southern Oscillation (ENSO), Reference Module in Earth Systems and Environmental Sciences. Elsevier 2013. http://dx.doi.org/10.1016/B978-0-12-409548-9.04082-3.

Vaughan, H., Waide, R.B., Maass, J.M., Ezcurra, E., 2007. Developing and delivering scientific information in response to emerging needs. Front Ecol Environ. 5 (4), W8–W11.

Vose, J.M. and Maass, J.M. 1999. A Comparative analysis of hydrologic responses of tropical deciduous and temperate deciduous watershed ecosystems to climatic change. In: C. Aguirre-Bravo and C. Rodríguez-Franco (comp). North American Science Symposium: Toward a Unified Framework for Inventorying and Monitoring Forest Ecosystem Resources. Guadalajara, México (November 2-6, 1998). USDA Forest Service Proceedings RMRS-P-12:292-298.